

# WHIM in superstructures

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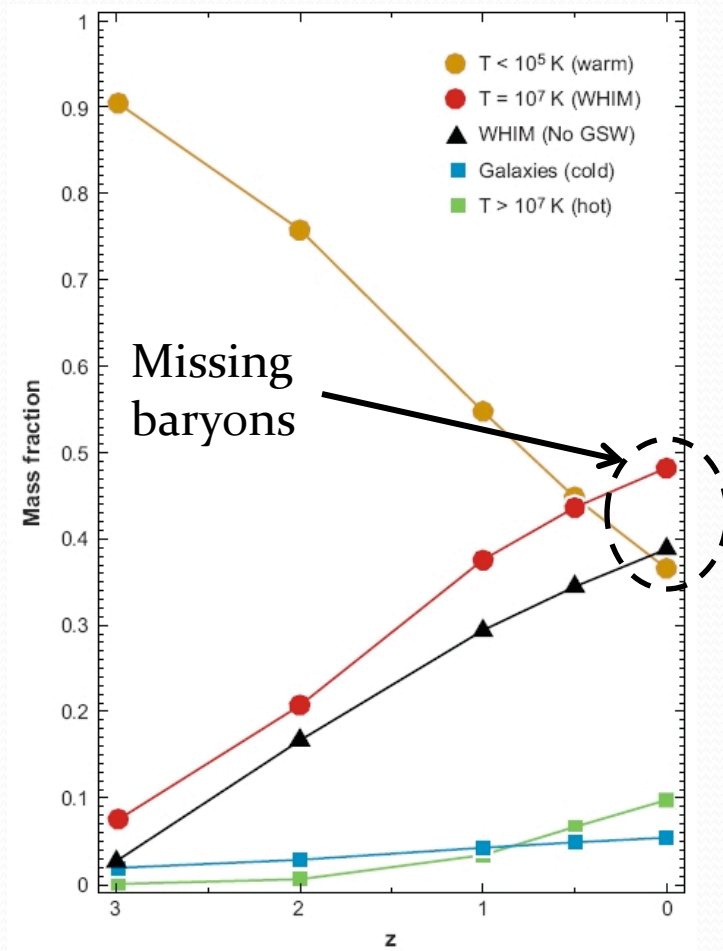
## Europe

- Maiolino R. (INAF-OAR)
- Mannucci F. (INAF-IRA-Firenze)
- Finoguenov A. (MPE)
- Gilli R. (INAF-OABO)
- Ferrara A. (SISSA)
- Schuecker P. (MPE)
- Tagliaferri G. (INAF-OAB)
- Gastaldello F. (Univ. Bologna/UCI)

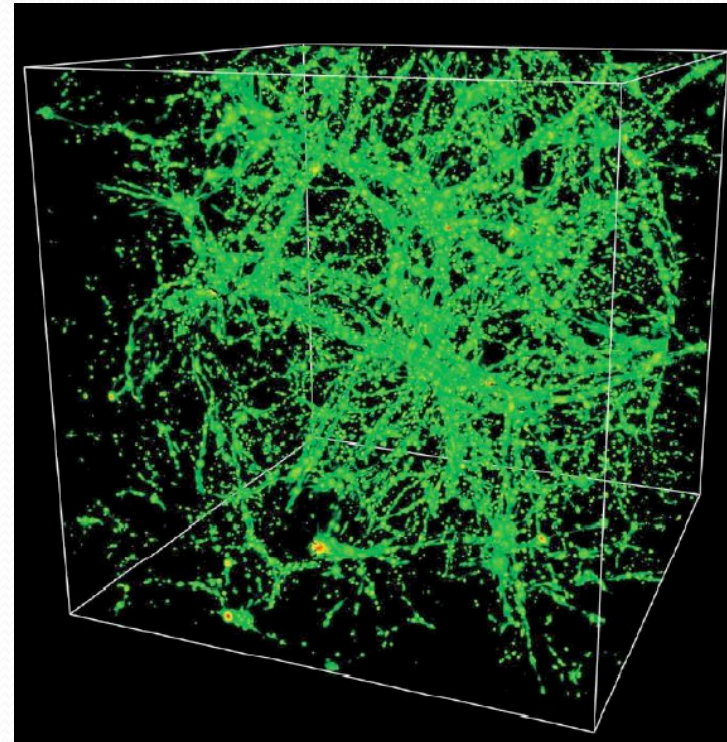
## USA

- Buote D.A. (UCI)
- Fang T. (UCI)
- Humphrey P.J. (UCI)

# The baryon history from simulations



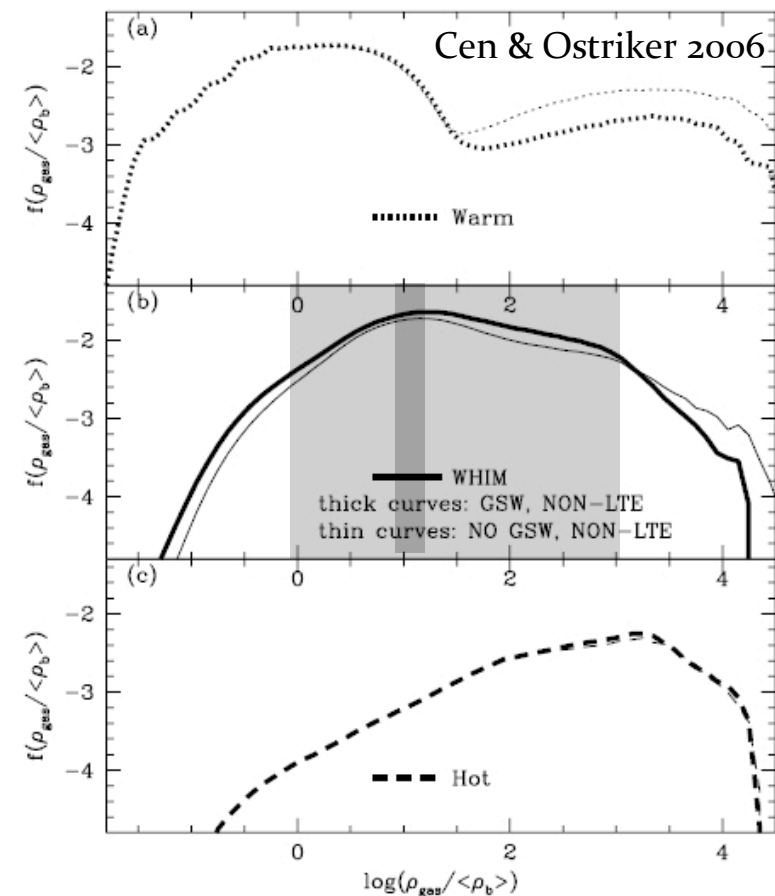
From cosmological simulations  
*Cen & Ostriker 2006*



# The Warm-Hot Intergalactic Medium (WHIM)

- Located in the non-virialized filamentary large-scale structure of the local ( $z < 1$ ) cosmic web
- Gas shock-heated during its infall in the large-scale structure gravitational potential
- Filaments size:  $25-5 \times 3-5$  Mpc
- Warm-hot  $T \rightarrow 10^5-10^7$  K
- Low density:  $10-20 \langle \rho_b \rangle$
- The bulk at overdensities  $1-1000 \langle \rho_b \rangle$

Cen & Ostriker 1999, Davé et al. 2001,  
Dolag et al. 2006, Cen & Ostriker 2006



# WHIM in superstructures

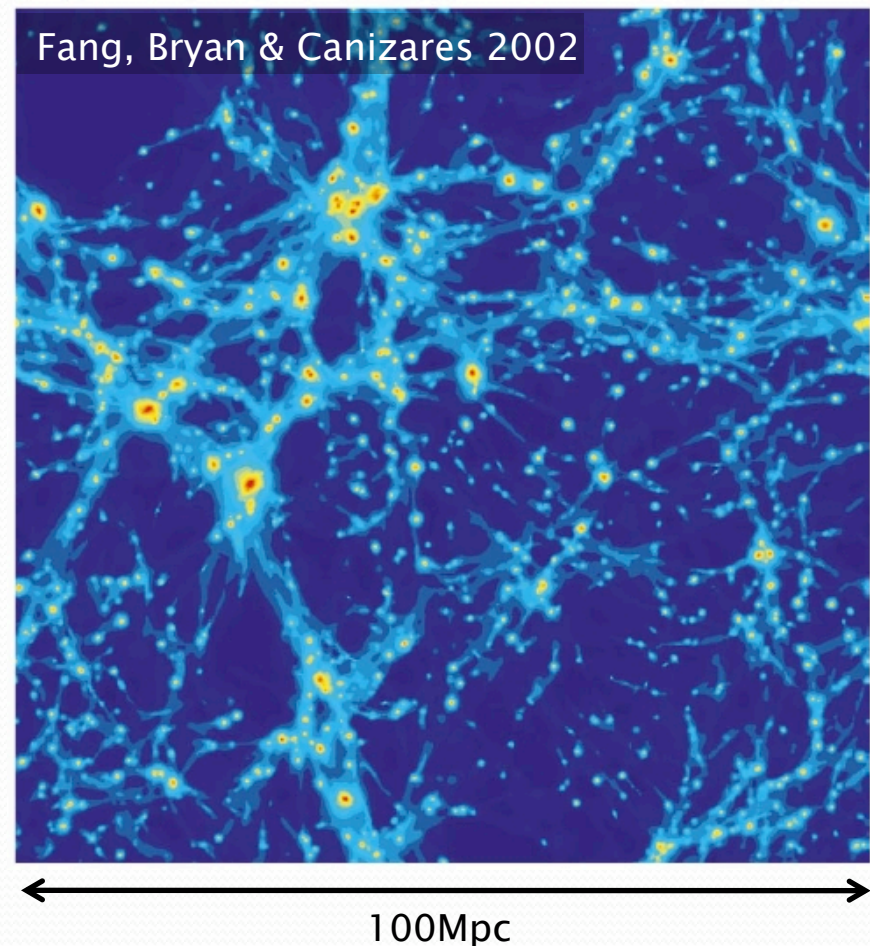
Large amounts of warm-hot  
gas distributed in filaments  
in supercluster sized  
large-scale structures

E.g.

Metal mass ( $M_Z$ ) contribution

$300-10^3 \langle \rho_b \rangle \rightarrow \sim 20\% \text{ of } M_Z^{\text{WHIM}}$

$600-10^3 \langle \rho_b \rangle \rightarrow \sim 10\% \text{ of } M_Z^{\text{WHIM}}$   
(Cen & Ostriker 2006)







# How to detect the WHIM

Mainly in the Far UV/soft X-rays

- Soft X-ray ( $< 1$  keV) imaging  $\rightarrow$  ROSAT, XMM
- FarUV/X-ray absorption lines from the most abundant ions (oxygen: OVI, OVII, OVIII, Ne ions, ... ) in the spectrum of bright background sources (the *X-ray forest*; Hellsten et al. 1998)  $\rightarrow$  Chandra and XMM gratings, FUSE, HST-STIS
- X-ray direct spectroscopy:
  - Line emission from the ions  $\rightarrow$  XMM, Suzaku
  - cluster soft excesses  $\rightarrow$  ROSAT, XMM, Suzaku



# Detecting WHIM in emission

Emission studies can probe the hotter ( $T > 10^6$  K) and denser ( $> 100 \langle \rho_b \rangle$ ) WHIM phase

Problems to deal with:

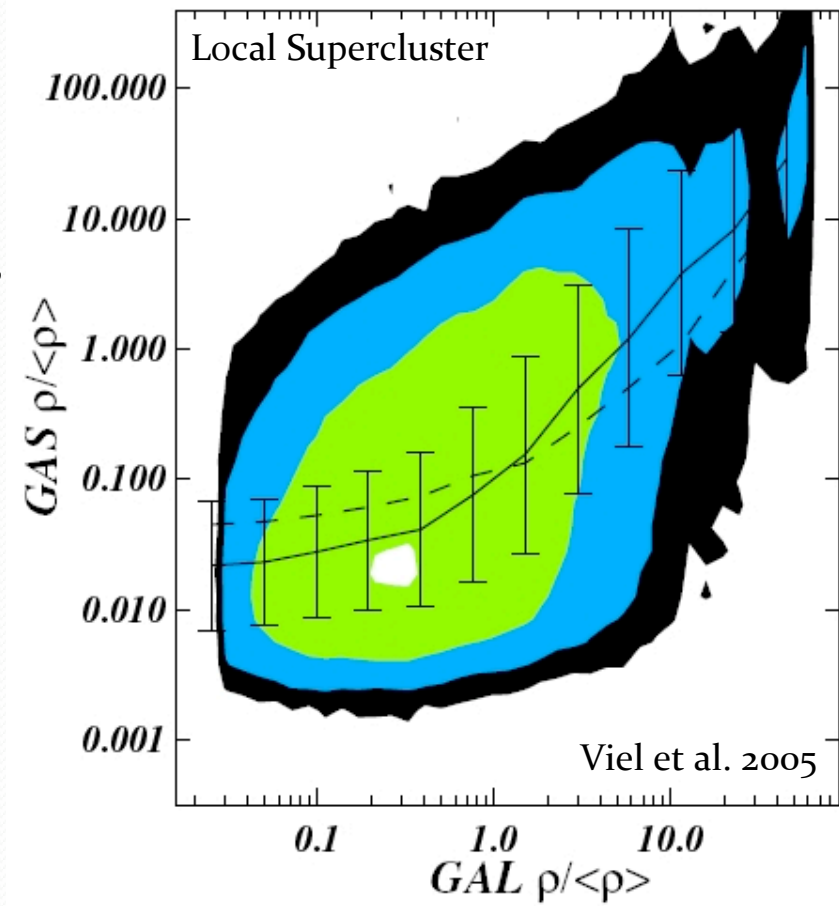
- Low surface brightness regions emitting in the soft X-ray energies ( $< 1$  keV)
- Galactic  $N_H$  (need low  $N_H$  regions)
- Lots of Galactic foregrounds and extragalactic backgrounds
- Large field of view (e.g. 3Mpc @  $z=0.1 \rightarrow 27$  arcmin)

# WHIM and galaxies in filaments

The dark matter large-scale structure gathers galaxies and gas



Gas and galaxies trace each others in filaments





# WHIM in emission studies

- Few claims of WHIM filamentary X-ray emission correlated with galaxy/clusters distribution

(E.g. Kull & Boehringer 1999, Scharf et al. 2000, Tittley & Enriksen 2001, Werner et al. 2008)

- Low/mid resolution detectors ROSAT, ASCA, XMM
- temperature  $\leq 1$  keV
- High dense regions (inter-cluster regions)
- Pollution by intracluster medium outskirts
- Sometimes no clear redshift determination from galaxies





# WHIM in the Warwick field

*Zappacosta et al. 2002*

Low  $N_{\text{H}}$  field ( $\sim < 10^{20} \text{ cm}^{-2}$ )

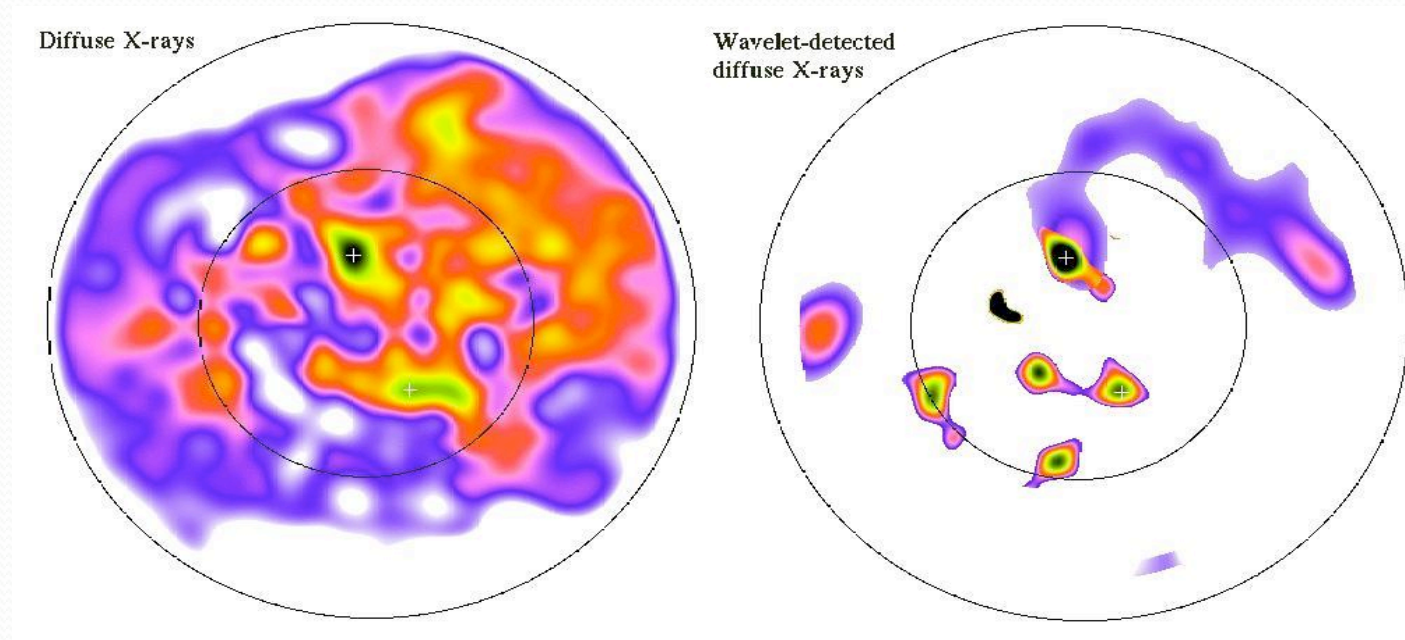
- Warwick et al. 1998 → detection of diffuse filamentary emission on several partially overlapping ROSAT PSPC pointings

Re-analysis of one of the ROSAT fields

Aims:

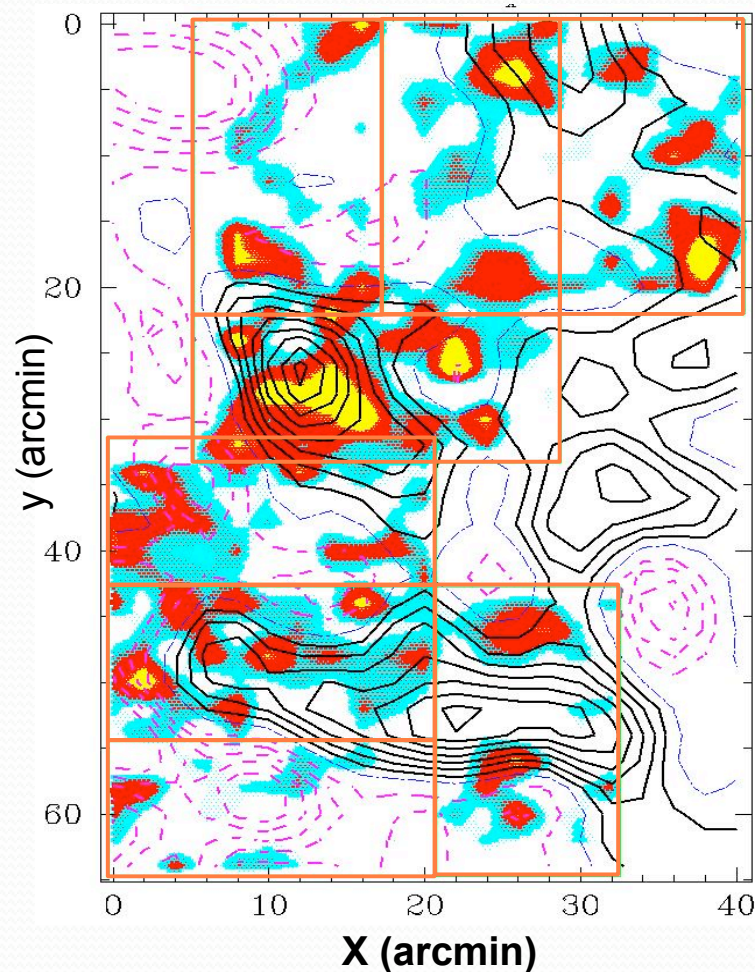
- Correlate diffuse emission with galaxy overdensity
- Redshift of the correlated structures
- Measure flux and spectral shape

# Diffuse emission in the soft X-rays



- 20ks ROSAT PSPC field (1/4 keV band) after point source removal
- **Extended structures detected**
- Structures in common  $\rightarrow 5\sigma$  significant
- ISM absorption correction from 21cm map do not affect the morphologies

# Galaxy/X-ray distribution



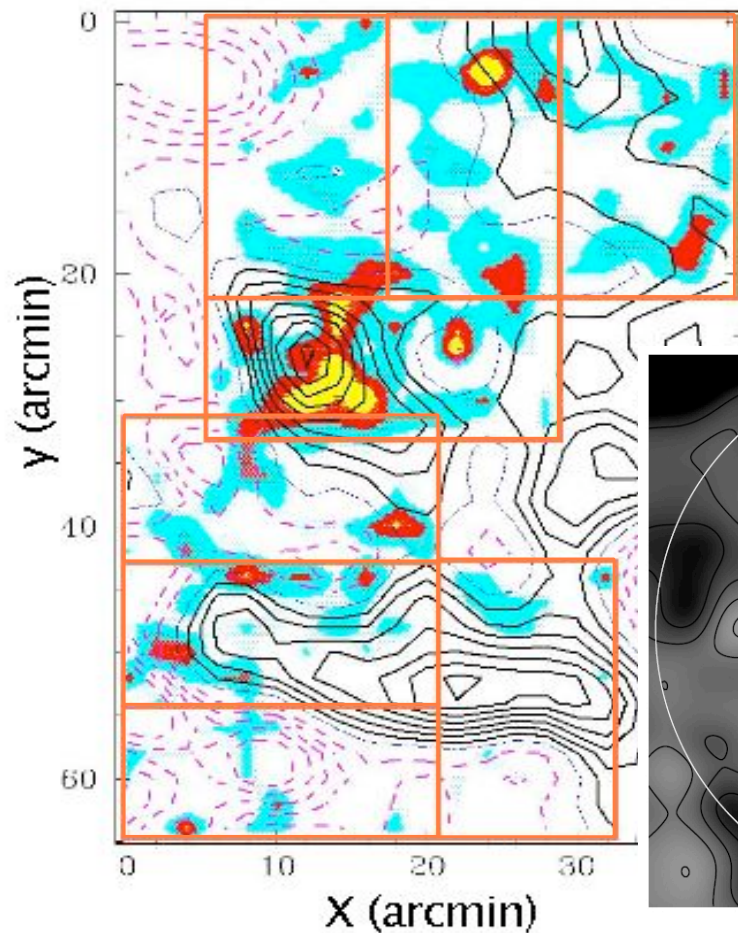
## Galaxy distribution

- optical observations obtained at Isaac Newton Telescope (Canary Islands)
  - central region of PSPC field of view
  - 5 photometric bands  $\rightarrow$  photo-z

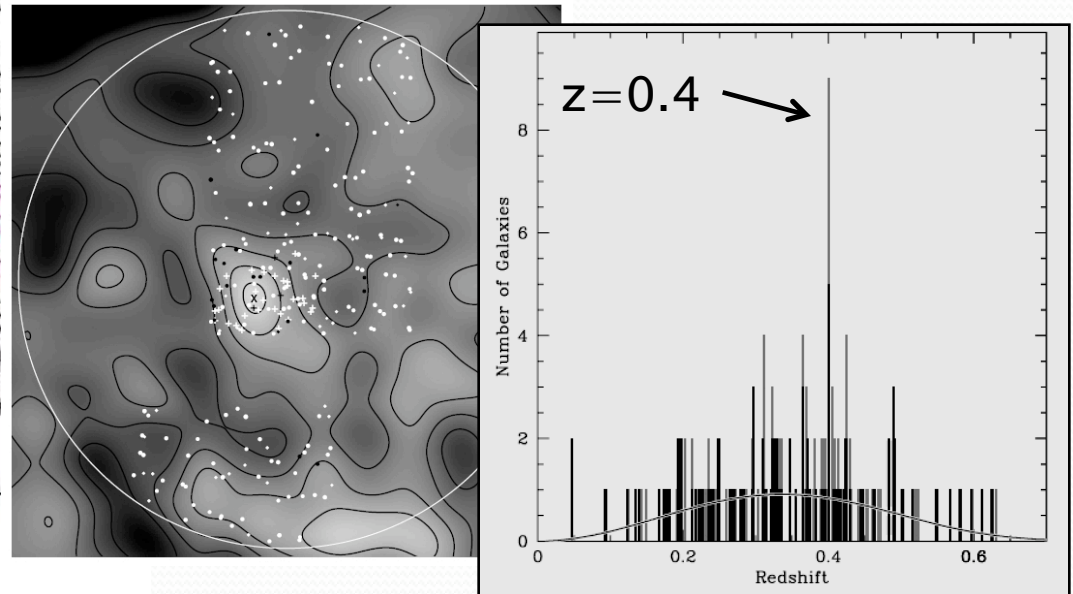
## Correlation X-ray/galaxies

- Projected galaxy overdensity coincident with the structure

# The redshift of the overdensity

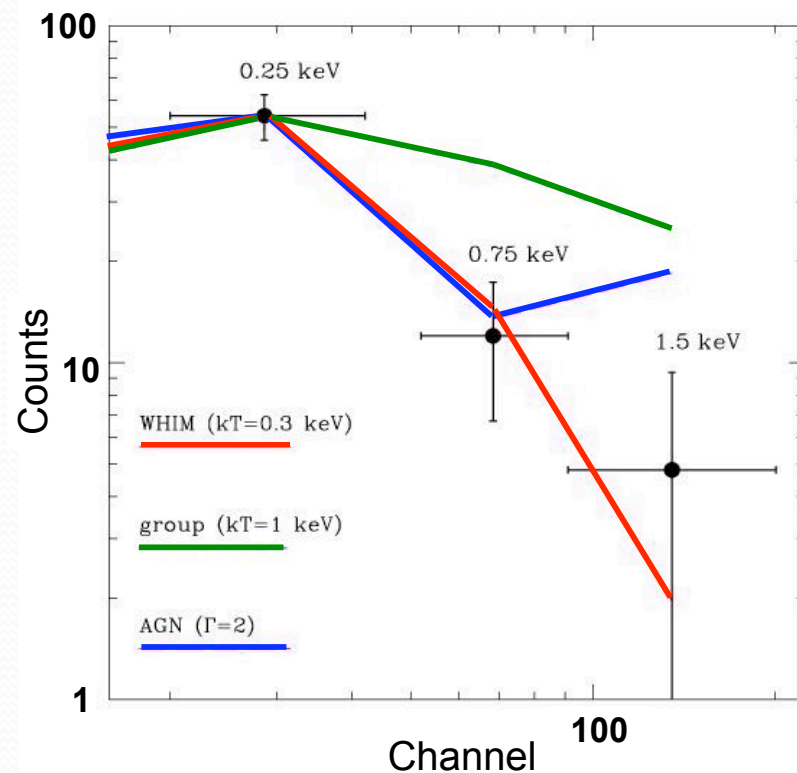


- Photometric redshifts:
    - galaxy overdensity significant at  $6\sigma$  in the range  $0.3 < z_{\text{phot}} < 0.6$ .
  - A later spectroscopic survey (161 obj)
    - $z_{\text{spec}} = 0.40$  (~20 obj)
- (Mannucci, Bonoli, LZ et al. 2007)





# Spectral shape of the structure



- spectrum consistent with WHIM:

$$T \sim 3-6 \cdot 10^6 \text{ K}$$

(assumed  $Z=0.05-0.3Z_{\text{sun}}$ )

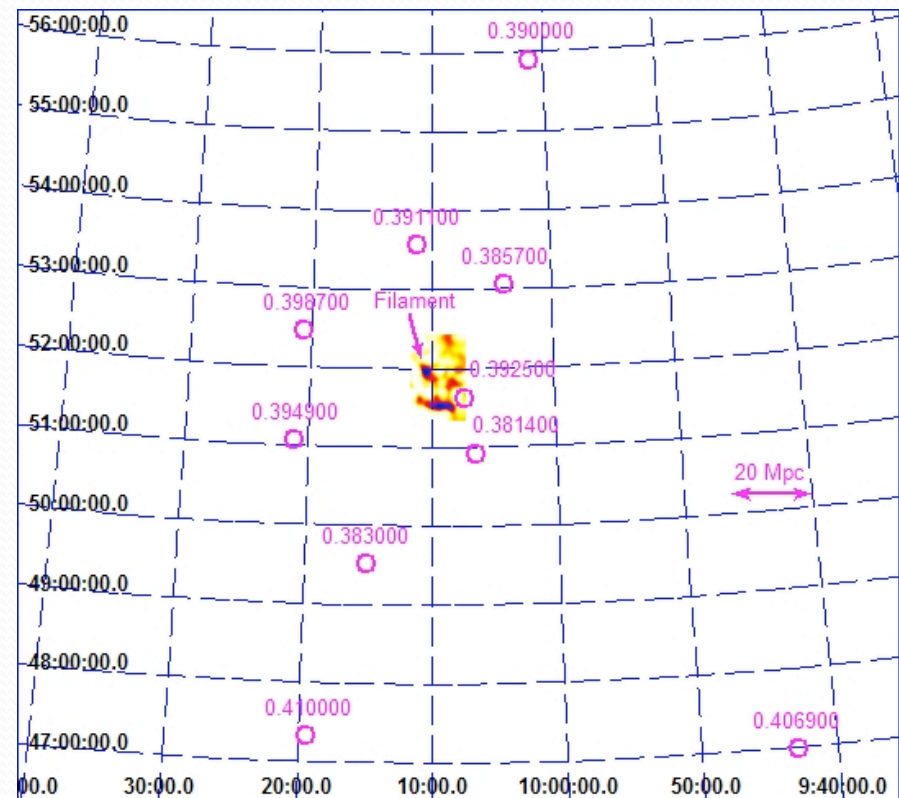
- group and clusters are too hot ( $T > 10^7 \text{ K}$ )
- unresolved type I AGNs are  $3\sigma$  inconsistent ( $\Gamma=2$ )

The flux (0.2-0.3 keV) is in good agreement ( $10^{-12} \text{ erg/s/cm}^2/\text{deg}^2$ ) with the simulations (*Croft et al. 2001*)



# Filament in a supercluster environment

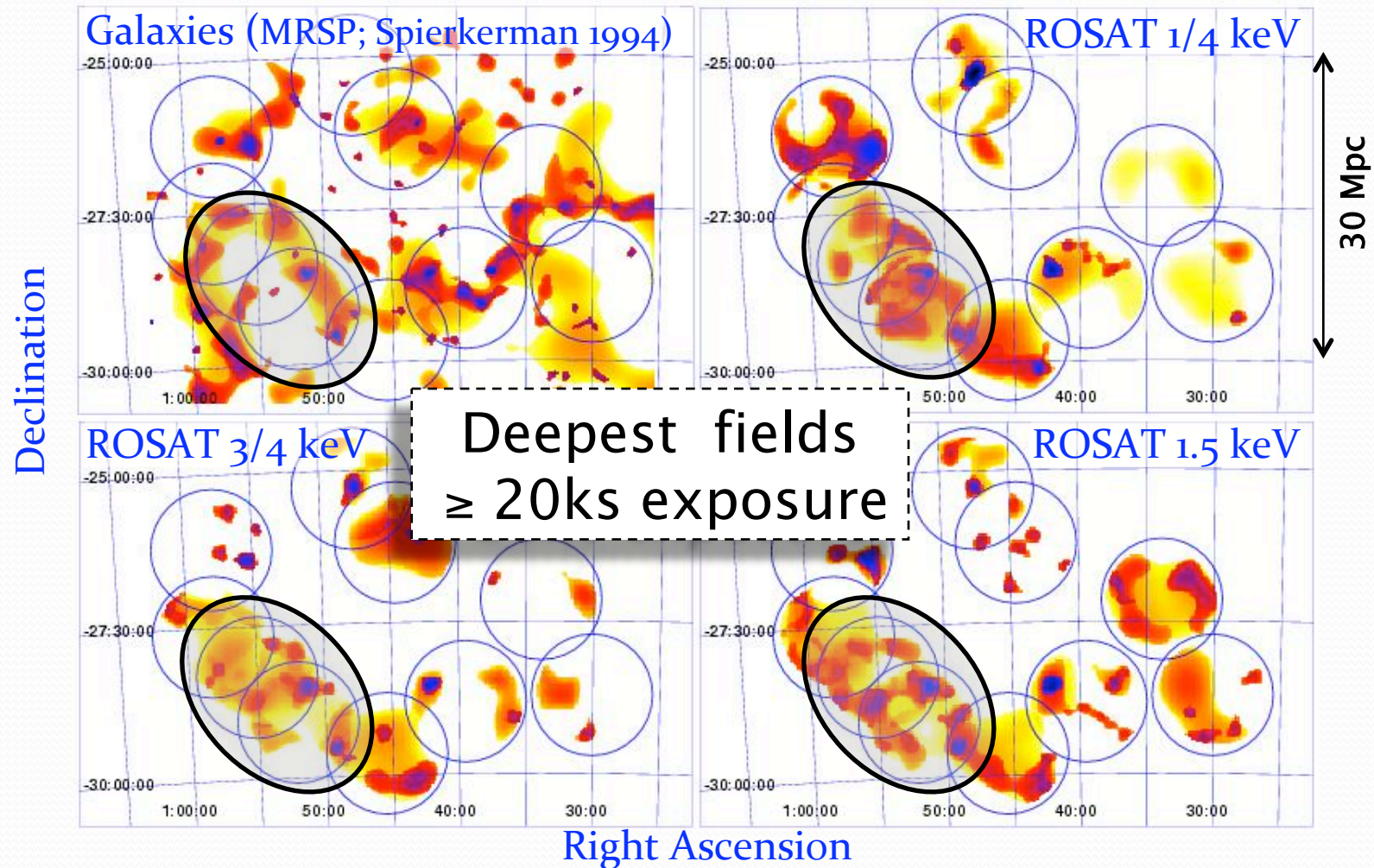
- Size  $> 6$  Mpc (@  $z=0.4$ )
- Overdensity:  $\sim 600 \langle \rho_b \rangle$  with large uncertainties  
(outskirts of groups at  $r_{500} \rightarrow \sim 1000 \langle \rho_b \rangle$ )
- 10 spectroscopically confirmed clusters/groups at  $z \approx 0.395 \pm 0.015$
- Supercluster environment ( $\geq 100$  Mpc)



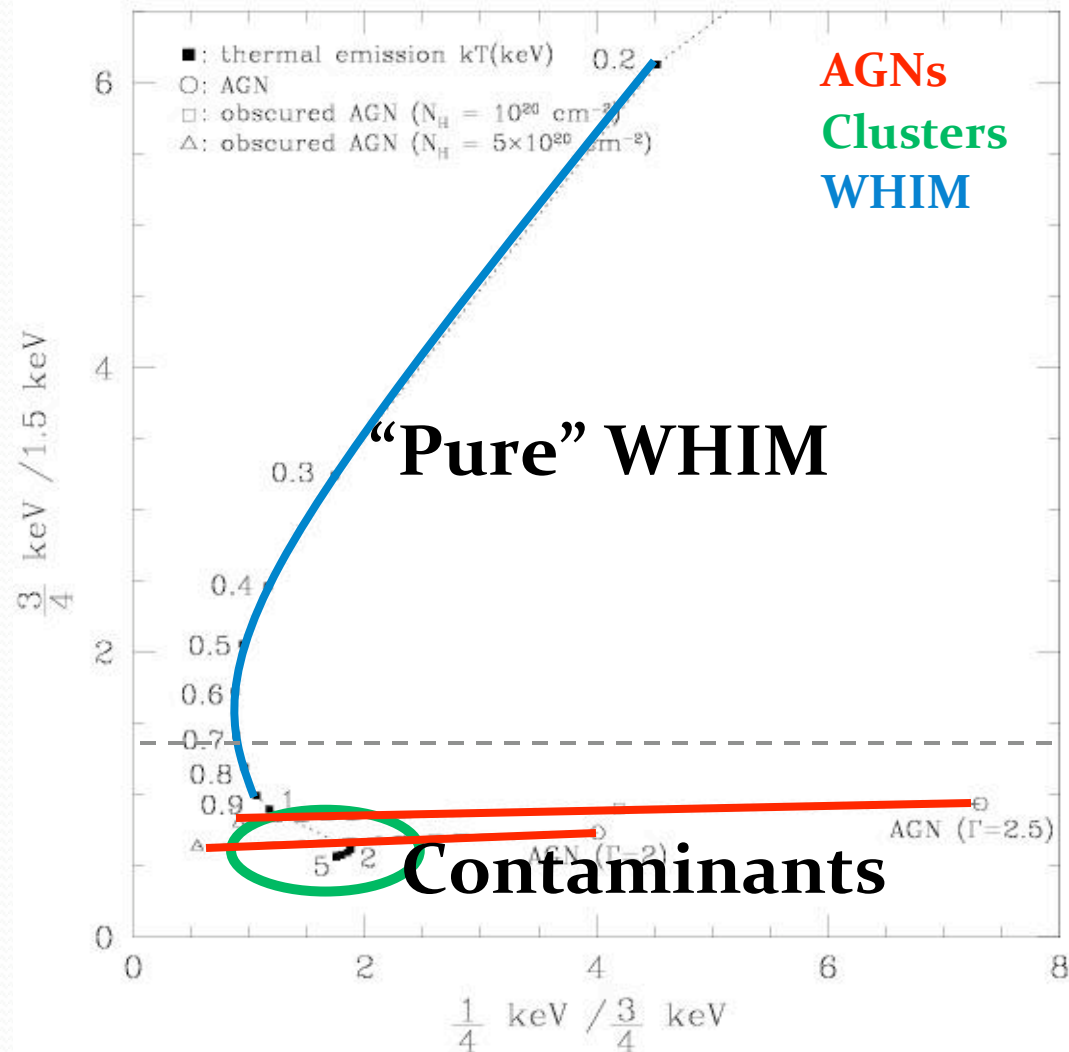
# WHIM signature in the Sculptor Scl

Sculptor Supercluster ( $z=0.1$ ) ,  $N_H \sim 1.5 \cdot 10^{20} \text{ cm}^{-2}$

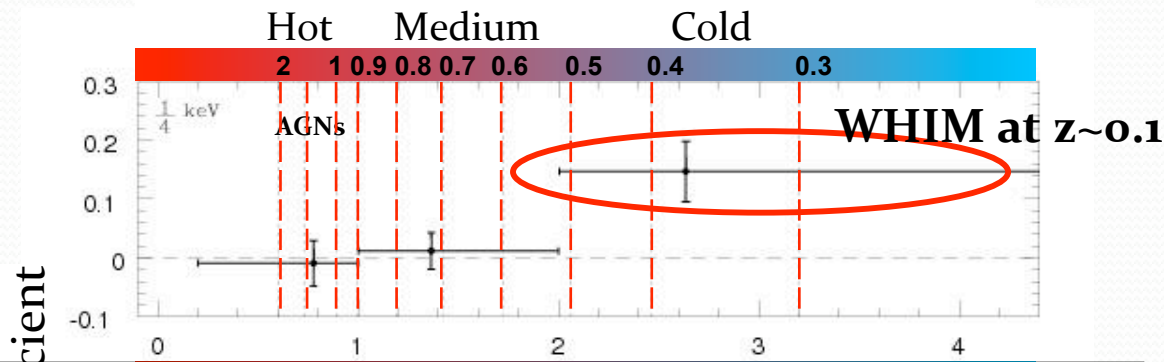
Zappacosta et al. 2005



# WHIM in the Sculptor Scl: color-color



# WHIM in the Sculptor Scl: correlation



Correlation ( $>3\sigma$  significant) between galaxy distribution and regions of X-ray emission which correspond to plasma with  $T \leq 5-6 \times 10^6$  K

Cannot be explained by correlations with:

- unresolved AGNs
- emission from group of galaxies or individual galaxies

**Evidence for warm-hot gas permeating the supercluster**

3/4 keV / 1.5 keV

# X-ray absorption spectroscopy: no WHIM detection so far

## Mkn 421 case

- Among the most luminous and intensely studied blazars
- X-ray high resolution spectroscopy absorption studies with Chandra and XMM with high quality grating data

### Pro WHIM

- Nicastro et al. 2005
- Williams et al. 2006

- Chandra detection
- XMM non detection  
(consistent with Chandra)

Disagreement  
between groups  
and satellites

### Against WHIM

- Kaastra et al. 2006
- Rasmussen et al. 2007

- Non detection with Chandra
- Non detection with XMM



# X-ray absorption spectroscopy: no WHIM detection so far

## PKS2155-304 case

- Among the most luminous and intensely studied blazars
- X-ray high resolution spectroscopy absorption studies with Chandra and XMM with high quality grating data

### Pro WHIM

- Fang et al. 2002
- Fang et al. 2007

- Chandra detection
- XMM non detection  
(consistent with Chandra)

Disagreement  
between groups  
and satellites

### Against WHIM

- Nicastro et al. 2002
- Rasmussen et al. 2003
- Cagnoni et al. 2004

- Non detection with Chandra
- Non detection with XMM

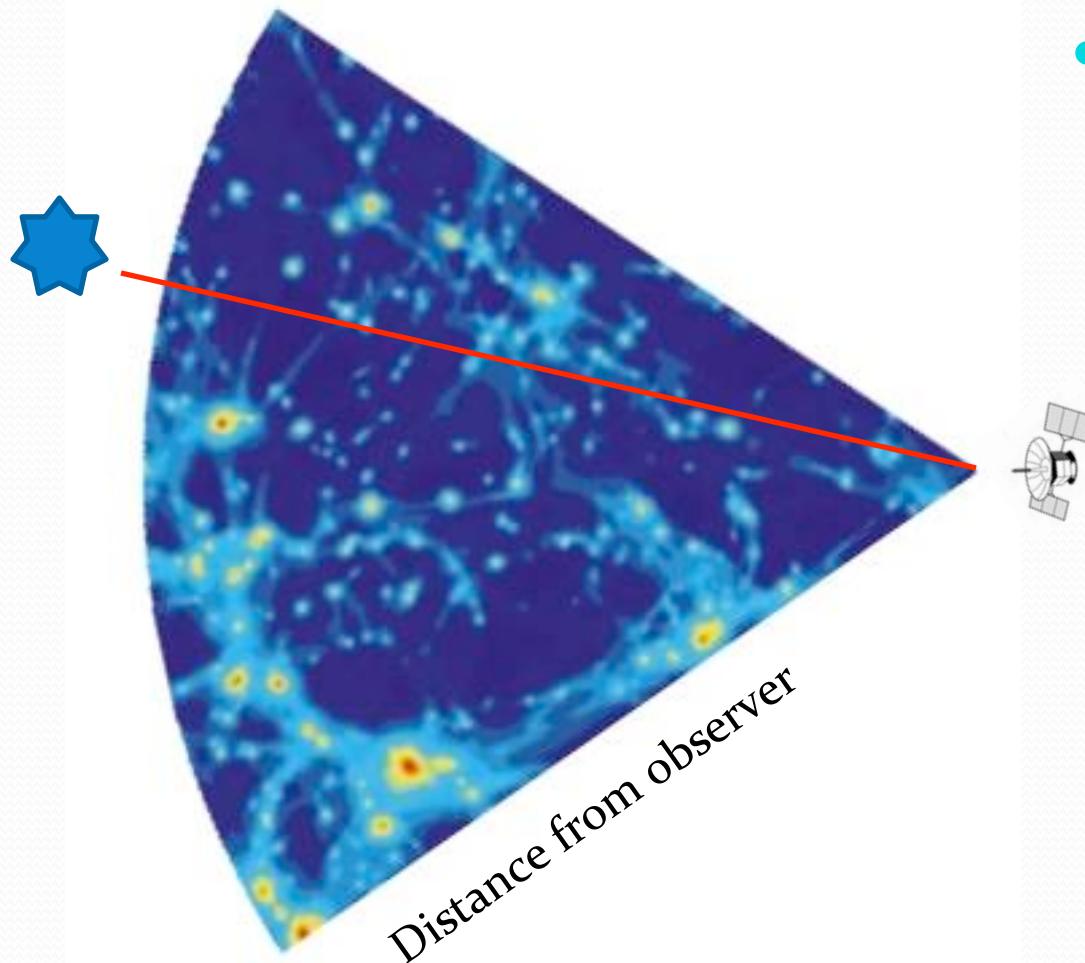
# Why WHIM has yet to be detected in X-rays

Different authors and different satellites have  
given controversial results so far

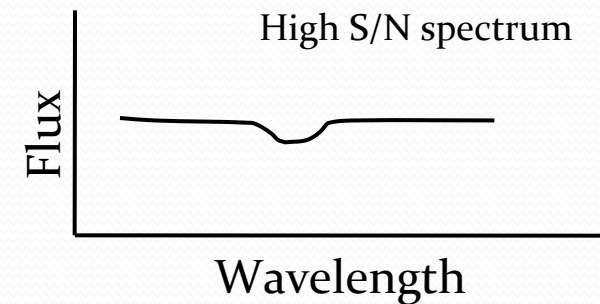


Details of the data analysis and statistical assessment  
are crucial for weak lines detection

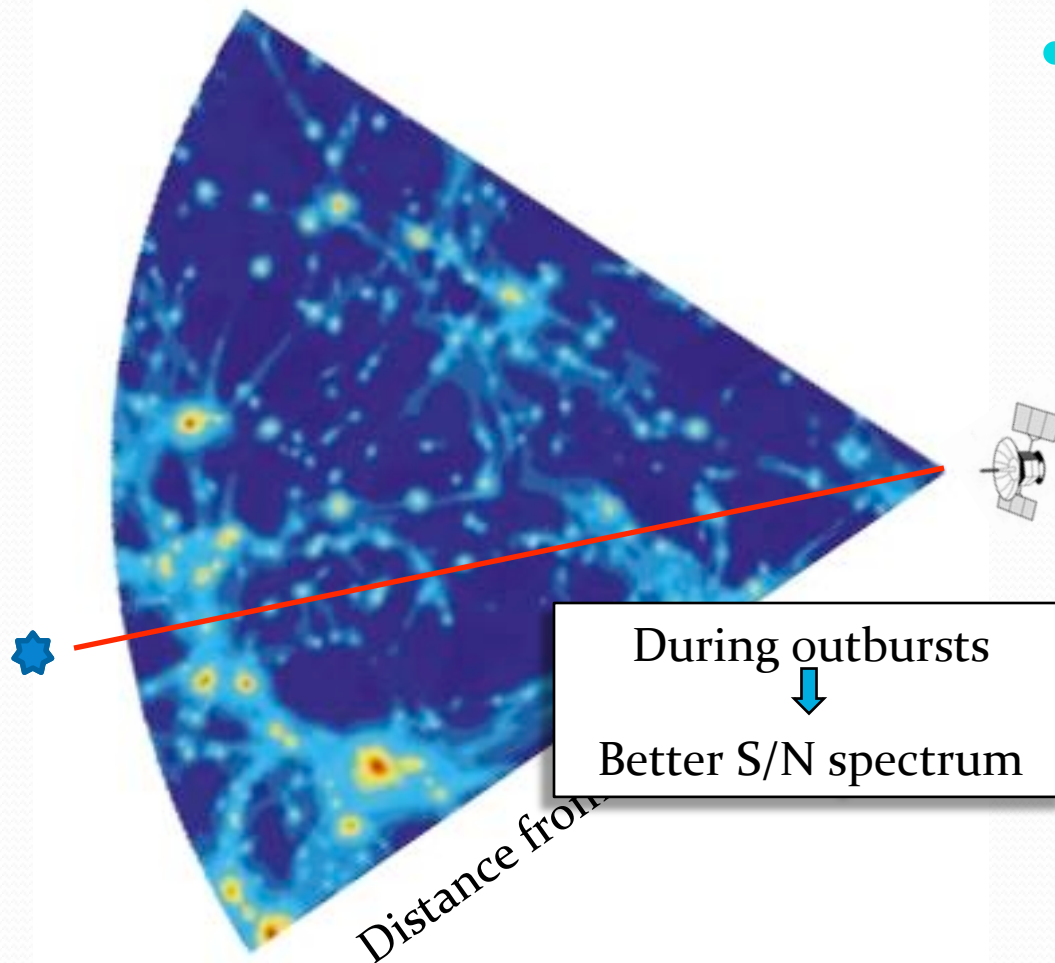
# Strategies for WHIM detection



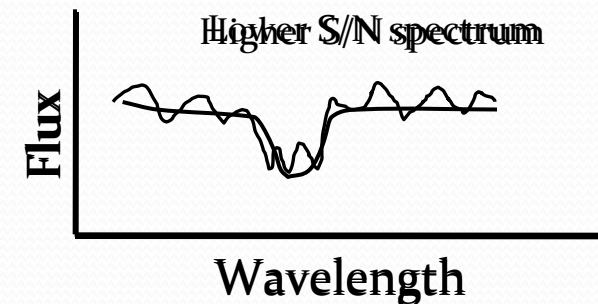
- Blind searches
  - Very bright AGNs
  - Very long exposures
  - Low density filaments  
→ weak lines



# Strategies for WHIM detection



- Targeted searches
  - Moderately bright AGNs behind superstructures
  - Lower exposure times
  - larger gas densities
  - *A priori* redshift knowledge
  - Higher metallicities→ stronger lines

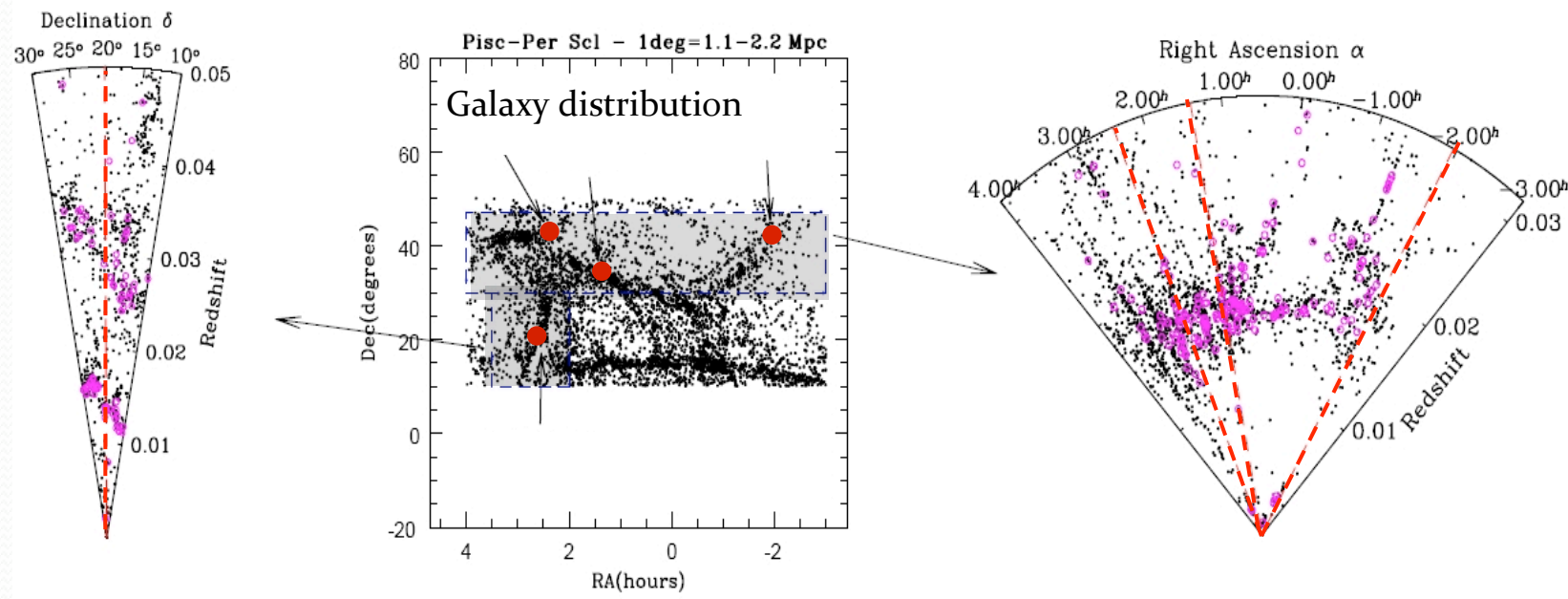


# WHIM in filaments: our strategy

Since 2005

Proposing TOO observations of blazars during their outburst state located behind local known large-scale unvirialized filamentary structures traced by the galaxy distribution to obtain a firm detection (i.e.  $5\sigma$ ) of the WHIM.

(approved in Chandra Cycle 7/8/9, XMM-AO6, PI: Zappacosta)





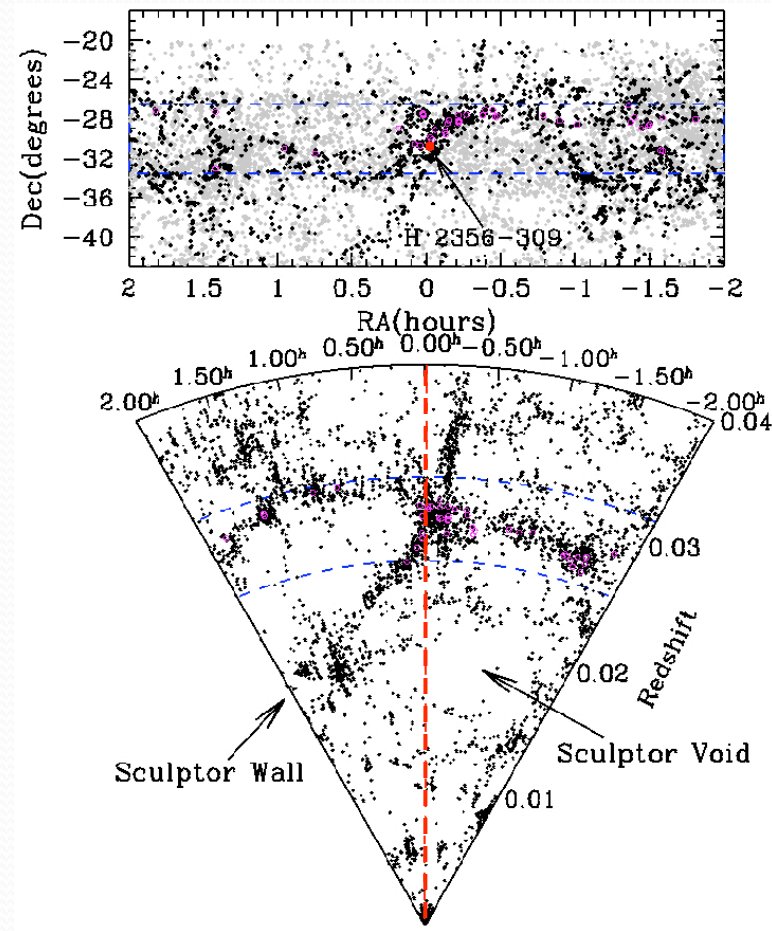
# The Sculptor Wall

- Blazar H2356-309 ( $z=0.165$ )
- Sculptor Wall  $z=0.03$  (@blazar location)

Observation triggered with both  
XMM and Chandra during two  
different short outbursts

- XMM observation ( $>40$  hours after the request of observation)
- Chandra observation ( $\sim 10$  hours after the request of observation)
- Source flux  $1.2\text{--}1.5 \times 10^{-11}$  erg/s/cm<sup>2</sup> ( $\sim$ quiescent state)

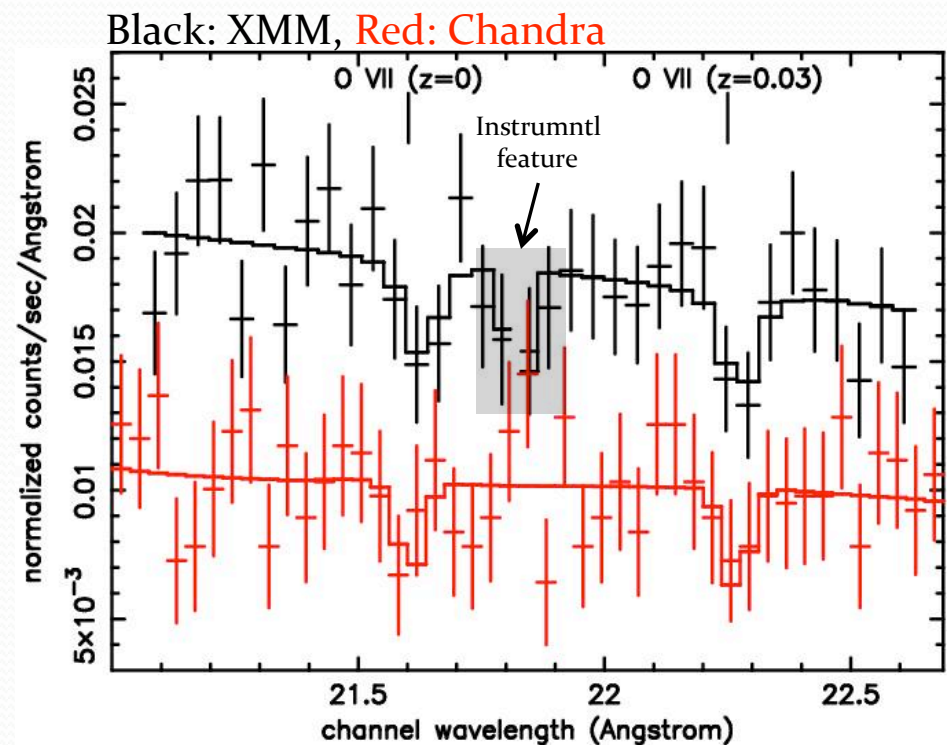
Nonetheless...



# OVII WHIM evidence

## From both XMM and Chandra

- Evidence of local and intervening OVII in **both** Chandra and XMM spectra
- The intervening OVII line is at the redshift of the Sculptor Wall ( $z=0.03$ )
- Joint OVII significance  $3\sigma$
- $N_{\text{OVII}}(z=0.03) = 9 \pm 4 \times 10^{15} \text{ cm}^{-2}$



Zappacosta et al. 2008 in prep.

# The future: a benchmark observation of WHIM

It will provide a  $5\sigma$  detection  
of OVII

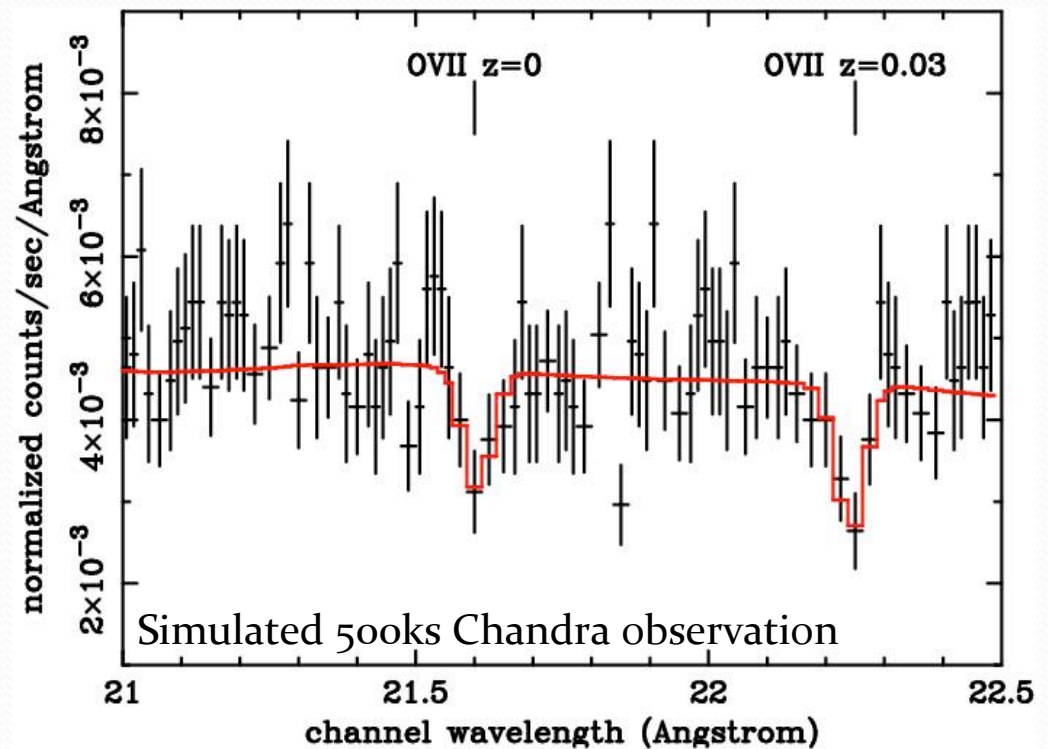


first firm WHIM  
detection

A non detection will provide a  
strong upper limit



Serious challenge  
for the theory  
(baryonic matter distribution, processes of metal  
enrichment)





# Conclusions

- WHIM is difficult to detect.... but we already knew that!
- WHIM in unvirialized structures can be detected in dense supercluster environment with data and satellites already available
  - Soft X-ray diffuse emission (Warwick field, Sculptor Scl)
  - X-ray absorption in background AGN spectra (Sculptor Wall)
- Galaxy distribution provides a valid signpost for the WHIM distribution in superclusters
- Characterization of supercluster environment more feasible than the bulk of 'missing baryons'
- Useful to characterize future observatories which will target mainly these dense regions in line emission